Accurate Spacecraft Positioning by VLBI Imaging

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Abstract VLBI is a radio astronomy technique with very high space angle resolution, and the Chinese VLBI Network has played an important role in the Chang'E series lunar mission. In the upcoming Chinese lunar and deep space missions, the ability to achieve higher resolution angular positions will be necessary. For these reasons, we have carried out research into accurate spacecraft positioning and have conducted several space vehicle phase-referencing positioning experiments using the Chinese VLBI Network and other VLBI antennas. This paper shows the VLBI spacecraft imaging position experiment results for the Chang'E lunar probes, the Mars Express probe, and the Rosetta probe. The results have validated phase reference VLBI with the milli-arcsecond level position resolution for deep space probes.

Keywords Phase reference VLBI, Chang'E lunar probes, MEX, Rosetta

1 Introduction

Very Long Baseline Interferometry (VLBI) has played an important role in spacecraft positioning during the past decades. Higher accuracy VLBI measurements will be necessary for the future of deep space explorers. Phase reference VLBI is a technique whose accuracy can reach the milli-arcsecond (mas) level or even higher. For this reason, it has been used in high accuracy spacecraft positioning [1]~[10].

China has launched probes for lunar exploration, and the positioning accuracy of the lunar spacecraft is on the order of 100 m (~50 mas) [11]. Future Chinese deep space exploration will require more accurate positioning results. For the research into high accuracy phase reference VLBI positioning, some experiments using lunar probes (CE-2, CE-3, and CE-5T1), the Mars Express (MEX), and the comet 69P probe (Rosetta) have been carried out.

In this paper, we give some VLBI phase reference experimental results for the deep space probes mentioned above.

2 VLBI Imaging Theory

According to the VLBI imaging theory (Figure 1), the brightness distribution of the observed target can be restored from observed visibilities sampled on the UV plane by the inverse Fourier transform [12]~[14]:

$$I(l,m) = \int\int V(u,v) e^{j2\pi(ul+vm)} dudv \qquad (1)$$

where the UV plane is a plane that is perpendicular to the line of sight, and l and m are the cosines of the target unit vector along the U-axis and the V-axis, respectively.

When doing phase reference VLBI, the observed target phase is calibrated using a nearby calibrator. Because the most common system errors will be removed, the accurate target position with respect to the calibrator will be obtained.

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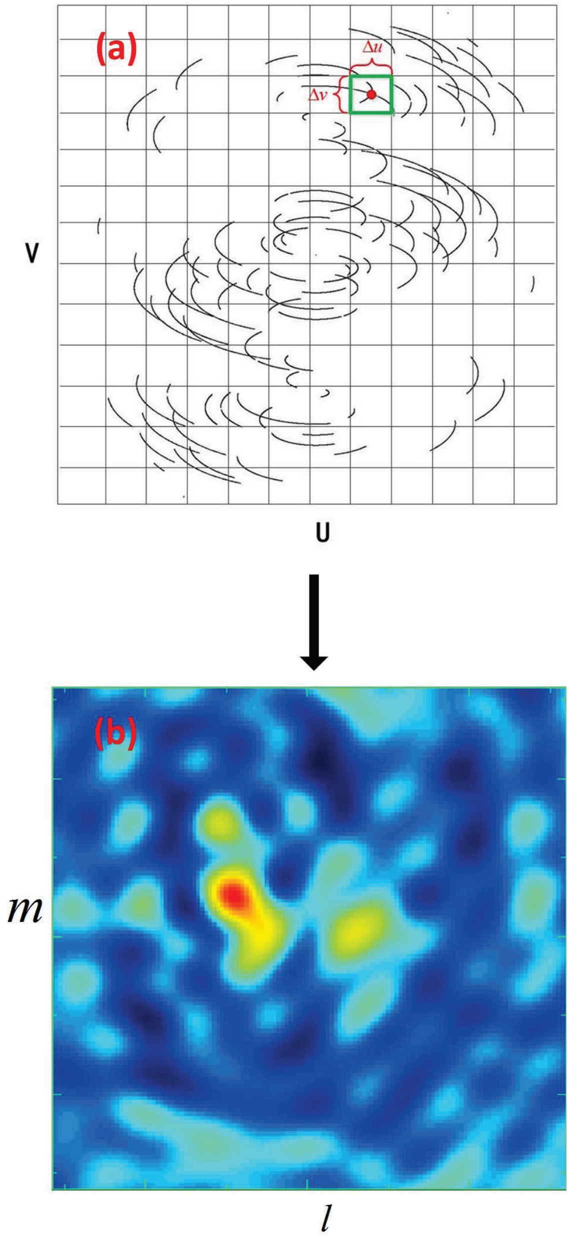

Fig. 1 UV sampling and raw image. (a) UV coverage; (b) raw image.

3 Data and Analysis

To study the spacecraft phase reference VLBI, several experiments (Table 1) have been carried out using the Chinese VLBI Network (CVN).

In these experiments, three CVN antennas joined the CE-2 observing; four CVN antennas joined the CE-3 and CE-5T1 observing; four CVN antennas and one Russian antenna (BADARY) joined the MEX observing; and three CVN antennas, three Russian antennas (SVETLOE, ZELENCHK, and BADARY), two New Zealand antennas (WARK12M and WARK30M), two South African antennas (HART15M and HARTRAO), three Australian antennas (KATH12M, YARRA12M, and HOBART26), and two German antennas (WETTZELL and WETTZ13N) joined the Rosetta observing. The imaging results are shown in Figure 2 through Figure 4. The brightest peak position of each image is the angular offset that is related to the target a priori position.

Table 1 Information of spacecraft phase reference VLBI experiments.

Spacecraft	Date (UTC)	Duration	Distance	Frequency
CE-2	2013-05	∼6h	$\sim 5\times10^7$km	S band
CE-3	2013-12	∼30h	$\sim 4\times10^5$km	X band
CE-5T1	2014-12	∼6h	$\sim 4\times10^5$km	X band
MEX	2015-01	∼2h	∼1.9895AU	X band
Rosetta	2015-09	∼10h	∼1.7889AU	X band

Figure 2 shows the imaging results of CE-2 and CE-3. Five CE-3 Rover relative positions were measured at the lunar surface sites A∼E. The CE-2 angular position accuracy is within the CE-2 orbital accuracy. The angular accuracy of the CE-3 Rover relative to the Lander is ∼0.5 mas, which is consistent with the position results measured with the onboard camera and the Inertial Measurement Unit (IMU).

Figure 3 shows the imaging results of CE-5T1 and Rosetta. The CE-5T1 and Rosetta position accuracies are within their respective orbital accuracies.

Figure 4 shows the imaging results of MEX. The top figure is the CVN result, and the bottom figure is the JIVE (Joint Institute for VLBI in Europe) result. The discrepancy between the CVN and the JIVE imaging positioning results is less than 2 mas. Both results are consistent with the MEX micro-arcsecond (μas) orbital accuracy.

4 Conclusions

In this paper, we showed the successful spacecraft phase reference VLBI experiments. Spacecraft phase reference VLBI can obtain mas-level positioning results. Phase reference VLBI does not need a specially

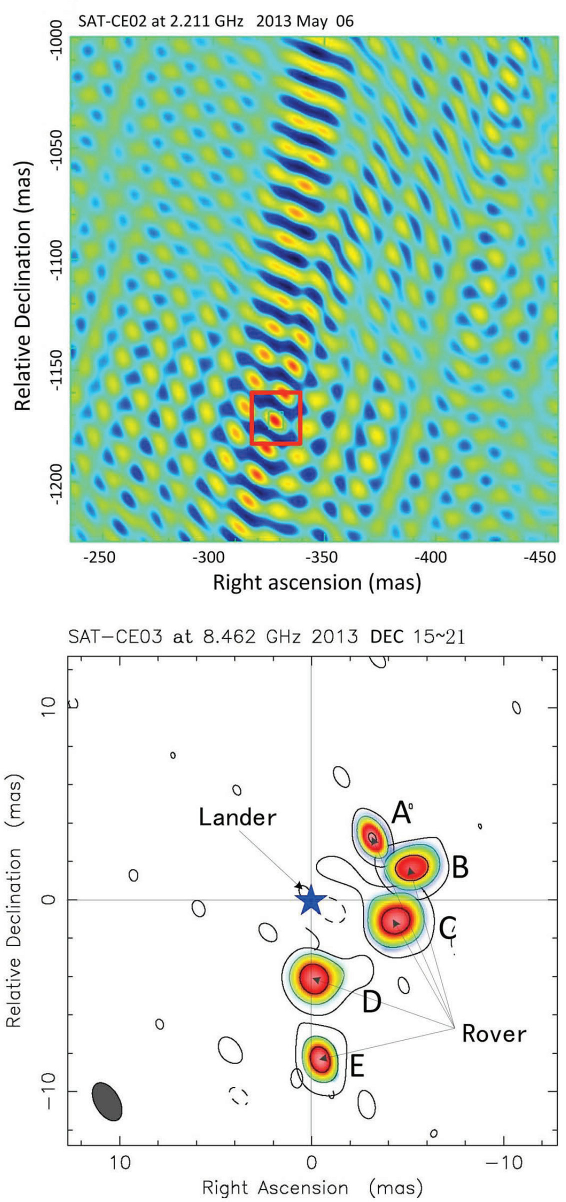

Fig. 2 Phase reference VLBI imaging results of CE-2 (top) and CE-3 (bottom).

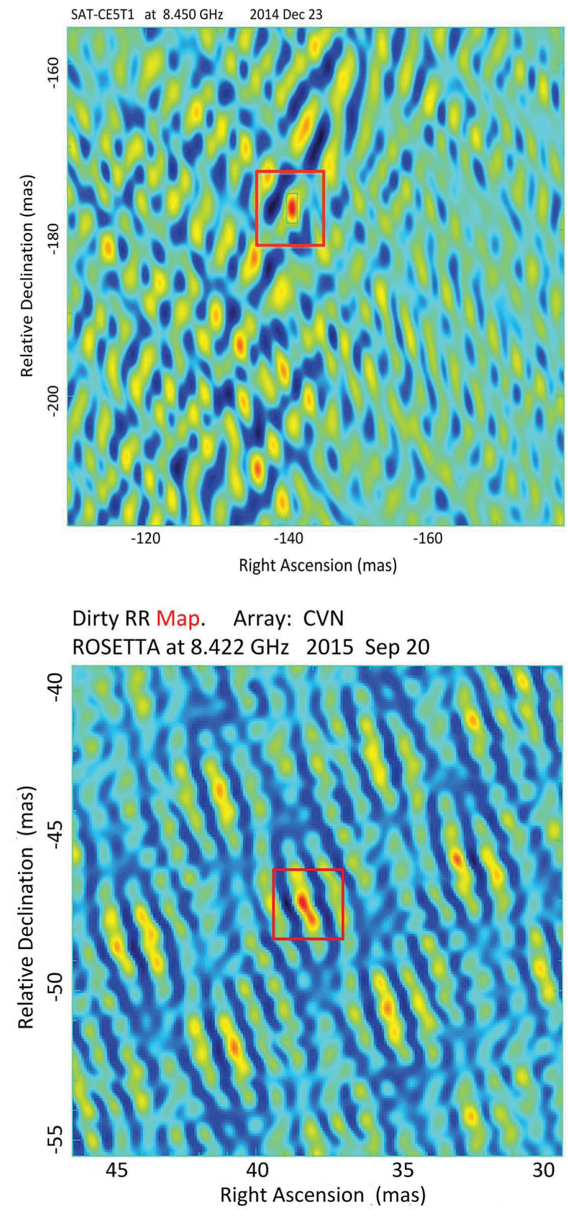

Fig. 3 Phase reference VLBI imaging results of CE-5T1 (top) and Rosetta (bottom).

designed radio beacon, and the observation sessions are short compared with the normal VLBI sessions. These are the merits of phase reference VLBI. The experimental results indicate that the VLBI phase reference can be used for spacecraft positioning of higher accuracy in the upcoming lunar and martian missions.

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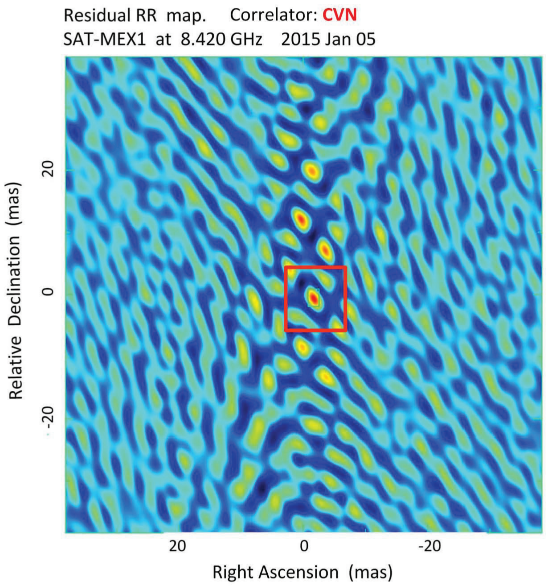

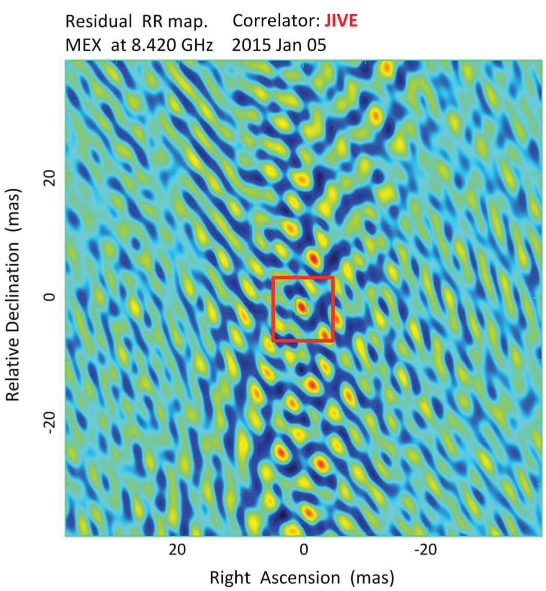

Fig. 4 CVN (top) and JIVE (bottom) phase reference VLBI imaging results of MEX.

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